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Advancing eHMI for powered wheelchairs beyond safety and communication: a pilot study on enriching social interaction through a co-design approach

Mohsen Rasoulivalajoozi [a,*], Morteza Farhoudi [b]

[a] Department of Individualized Program, Concordia University, Montreal, Quebec H3G 1N2, Canada
[b] Design Department, Ontario College of Art & Design University, Toronto, ON M5T 1W1, Canada

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ABSTRACT

Background: Enhancing safety and communication while minimizing unwanted attention is key for wheelchair external Human-Machine Interfaces (eHMIs). This study aims to introduce an interface to enhance eHMIs for powered wheelchairs, improve external communication, and enhance positive social interactions in challenging urban situations.
Methods: A co-design approach was adopted, centering wheelchair users (WUs) in a two-step methodology. First, data were collected through a qualitative survey to define criteria, which informed themes for focus group discussions. These themes guided the ideation process. Eighteen participants, including WUs and experts in cognitive psychology, physiotherapy, and design, were involved. Concepts developed in ideation sessions were analyzed using the Analytic Hierarchy Process. A prototype was then developed to be assessed by both WUs and pedestrians through a structured questionnaire.
Results: According to the analysis, four themes were identified: I. *Streamlined Information in Interaction*, II. *User-Centric Safety Feedback*, III. *Harmonious and Minimalist Interaction Design*, and IV. *Effortless Integration and Production*. Regarding these themes, a table with design suggestions and implications was introduced. Ultimately, five interface concepts were proposed, with Concept 2, ‘WheelSafe Illumina’ (41.3%), and Concept 1, ‘WheelGlow Assist’ (28.1%) emerging as top priorities, both featuring a shell structure. Concept 2 was developed for prototyping. The feedback from the experiences of both WUs and pedestrians indicate that the proposed eHMI may enhance perceived communication and safety without drawing negative attention.
Conclusion: Integrating eHMI into a shell structure improves functional communication while also minimizing unwanted attention toward WUs—an often-overlooked issue in previous research that our co-design approach identified and effectively addressed.

1. Introduction

Operating a wheelchair in an urban setting is challenging due to complex interactions with drivers and pedestrians, making it difficult to navigate crowded sidewalks and intersections safely. Implementing external communication features on wheelchairs can

* Corresponding author at: Department of Individualized Program (INDI), Concordia University Research Chair, (IdeasBe), Sir George Williams Campus 1455 De Maisonneuve Blvd W. Montreal, (QC) H3G 2V4, Canada.
E-mail address: mohsen.rasoulivalajoozi@mail.concordia.ca (M. Rasoulivalajoozi).

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help users move safely without communication barriers or ambiguity, especially in negotiable situations where clearly signaling their intent is crucial (Dey et al., 2021). This would reduce their travel burden and enhance their independence in mobility (Zhang et al., 2024). User-device interfaces and external Human-Machine Interfaces (eHMIs) play a pivotal role in empowering wheelchair users (WUs) to control their wheelchairs, significantly affecting their communication with their surroundings (Frank et al., 2010; Kim et al., 2022; Bizier et al., 2016.). Particularly, they facilitate indirect negotiation with pedestrians and car drivers.

Pedestrians can directly signal their intent to cross using eye contact and gestures with drivers (Dey et al., 2021; Dey & Terken, 2017). However, WUs, particularly those with physical limitations, such as restricted head and neck mobility, can face challenges in employing basic non-verbal communication methods, such as eye contact (Henje et al., 2021). This approach may convey ambiguous signs, depending on the severity of their disabilities, leading to potential safety challenges. Likewise, those with speech impairments may struggle with verbal communication, impeding interaction with pedestrians for assistance. In discussions about eHMI, most systems rely on a single modality, potentially overlooking the requirements of individuals with sensory impairments, including vision or hearing impairments (Dey et al., 2020). In ideal situations, eHMIs for individuals with minimal mobility impairments are often installed on mobility scooters, modeled after conventional car headlights, taillights, and flashers. However, WUs with more significant mobility impairments navigate diverse settings, routes, and social interactions, requiring specialized eHMI features.

In negotiable situations, where WUs need to convey intentions, such as signaling turns or indicating right of way, their powered wheelchair (PW) can create misconceptions (Brandt et al., 2004). Bystanders may mistakenly believe these users do not require negotiation or assistance, often due to the assumption that advanced wheelchair technology makes them fully self-reliant. This challenge may be exacerbated by socio-psychological phenomena like the bystander effect (Latané & Darley, 1970), where individuals are less likely to offer help to WUs when others are present. To date, most solutions have implemented ground-light projection systems to address safety and communication needs. However, these systems have often led to negative social reactions (Zhang et al., 2024; Jiang et al., 2022; Dey et al., 2021; Wang et al., 2018), such as drawing unwanted attention to WUs (de Costa et al., 2010; Barbareschi et al., 2020; Lanutti et al., 2015)—that is, attracting excessive or inappropriate public focus that makes users feel self-conscious, stigmatized, or socially exposed. This phenomenon may work as a barrier to social acceptance and integration.

This multifaceted challenge demands both an interdisciplinary perspective and co-design to address communication dynamics in wheelchair use. An interdisciplinary approach integrates the psychological, social, and design aspects of eHMIs, while co-design incorporates WUs' voices and concerns, ensuring their preferences and motion intentions are effectively conveyed to drivers and pedestrians. In line with this, we aim to introduce considerations for eHMI in PWs and present an external interface prototype developed through a co-design process. In this study, while the interface should focus on enhancing intent communication, and safety, it is worthwhile to explore alternative non-projection eHMI to mitigate unwanted attention, improve social acceptance, and enhance positive interactions for WUs in dense urban environments. Accordingly, we seek to answer research question: How can a wheelchair eHMI enhance intent communication and safety while improving social acceptance and reducing unwanted attention? Finally, we assess the effectiveness of our prototype using the evaluation models. This study offers the following contributions: 1) The proposed themes and considerations can serve as a framework for design experts in care to address the needs of various types of mobility aid users; 2) The proposed concepts enable engineers and human–computer interaction (HCI) experts to examine how social communication dynamics can be integrated with safety engineering considerations.

2. Literature review

eHMIs, commonly used as communication aids in automated vehicles (AVs) and pedestrian interactions (Holländer et al., 2021), facilitate communication of the vehicle's status, and intentions (Lim & Kim, 2022). These interfaces address the communication gap arising from the absence of traditional cues like eye contact and gestures, leading to a more positive perception of AVs compared to conditions without eHMI (Faas et al., 2020). eHMIs, classified as physical, auditory, or visual (Dey et al., 2020; Zhang et al., 2022). Among these, external interaction screens, matrix lights, and projection interfaces are commonly used because of their versatile interactions with diverse road users (Jiang et al., 2022). Common visual communication modalities generally include emulating human driver cues (Eisma et al., 2020), as well as textual, graphical (Bazilinskyy et al., 2019), lighting, and projection interfaces (Zhang et al., 2024; Dey et al., 2021). These visual modalities can be designed and organized in specific ways, to provide mutual understanding between users and pedestrians. For instance, when eHMI signals match vehicle movements, drivers experience fewer crashes and pass faster than situations without eHMI (Rettenmaier et al., 2020). These findings indicate that eHMI facilitates effective communication, reduces uncertainty in intention estimation, and prevents accidents.

Although eHMIs are widely recognized for their value in AVs, their application in other modes of transportation, such as for cyclists and WUs, has been limited and has not been extensively studied in eHMI research (Dey et al., 2020; Zhang et al., 2022; de Winter & Dodou, 2022). In this context, similar to cyclists, WUs engage with AVs in dynamic situations, necessitating eHMIs visible from all sides (Vlakveld et al., 2020), as they may face safety and communication challenges, particularly at higher speeds. Concerning pedestrians, predicting their behavior is also challenging, due to its dynamic nature, lack of training, and occasional rule-breaking tendencies (Carmona et al., 2021). Therefore, here a well-designed eHMI can offer advantages such as complementing implicit communication, and potentially enhancing overall performance and increased comfort levels (Chang et al., 2017; Habibovic et al., 2018). In one case, it is found that explicitly conveying a wheelchair's movement intentions, using methods like ground-projected light paths or red arrows, significantly improved interaction smoothness and pedestrian cooperation (Watanabe et al., 2015). In another recent study introduced an on-ground light projection-based eHMI for wheelchairs using automated driving system (ADS) technology, which improved motion intention clarity and appeal (Zhang et al., 2024). However, critiques of ground-projected light persist. For example, participants noted that projections were insufficiently visible in bright light and expected better performance in low light or indoor environments.

Concerns were also raised about projections' effectiveness on various terrains and their compatibility with existing accessibility infrastructure. Some users worried that on-ground projections might be difficult for passing vehicles to see, potentially leading to distraction, navigation challenges and unsafe situations caused by blind spots. The performance of wheelchairs in crowded areas and on challenging terrains, such as steps or uneven surfaces, was deemed crucial for safety and trust. There were concerns that constant focus on projections during autonomous driving could lead to overlooked environmental risks (Zhang et al., 2024). Considering these challenges in user experiences, it is worth exploring how alternative eHMI solutions can address these concerns.

2.1. eHMI: Social perceptions

WUs sometimes view their wheelchairs as an extension of their body (de Costa et al., 2010; Blach Rossen et al., 2012), which can attract more negative attention if the technology is highly noticeable (Barbareschi et al., 2021). Their interactions with the outside world influence both their self-perception and how others perceive them, making it crucial to avoid drawing unwanted attention to their disability (de Costa et al., 2010; Barbareschi et al., 2020; Lanutti et al., 2015). While wheelchairs are vital empowering tools, they also serve as a visible sign of disability, attracting unnecessary attention and potentially leading to social stigma (Barbareschi et al., 2021; Rasoulivalajoozi et al., 2025a). To avoid this issue, WUs often prefer visual over auditory communication in their daily interactions (Asha et al., 2021). An innovative design can provide a better user experience and reduce the association with stigma compared to a traditional wheelchair (Carneiro et al., 2017; Mokdad et al., 2018; Faraji & Valajoozi, 2014). In this regard, one study introduce an interface using laser projections and light displays on the street (Asha et al., 2021). The assessments showed that explicit interfaces could enhance interaction, but despite initial designs still lacked empathy and sensitivity, potentially drawing undue attention. Similarly, another study introduced on-ground projection light eHMIs with non-intrusive interaction methods. These included timed appearances, disappearing components, and customizable switches to minimize space use and attract attention only in emergencies (Zhang et al., 2024). Nevertheless, some participants reported that projections still drew undue attention. Additionally, auditory cues might cause stress due to excessive focus on the WUs. Despite the real-time interactivity and benefits of light projection eHMIs, which enhance trust and effectively convey users' emotions and intentions, they still attract more undue attention than traditional manual methods. To date, there is still a gap in exploring alternative eHMI solutions for wheelchairs that address social aspects and minimize unwanted attention.

2.2. eHMI: A framework for enhanced interaction of WUs

The aforementioned challenges associated with eHMIs in road communication, safety, and social interaction can be tracked in three key arguments presented by Joost de Winter and Dimitra Dodou (de Winter & Dodou, 2022): 1) the dominance of implicit communication in pedestrian- Automative vehicle (AV) interaction and the absence of a clear social interaction void to be filled, 2) the existence of a diverse range of eHMI concepts lacking standardization and consensus, 3) the potential for negative effects like distraction, confusion, and overreliance. Therefore, it is initially required to adopt a comprehensive framework to mitigate these potential challenges. To this end, Bingqing Zhang et al. offered design implications in a co-design session involving WUs and designers for shared control interaction interfaces of wheelchairs (Zhang et al., 2022). These implications highlight three primary pillars in eHMI for wheelchair design: 'Empathy, embodiment, and social acceptance,' 'Situational awareness and adaptability,' and 'Selective information management.' We aim to integrate these aspects as the theoretical framework into our research process to develop an alternative eHMI that addresses the limitations identified in existing literature. Each pillar addresses key criteria for developing eHMIs and aligns with our research question. Specifically, 'Empathy, embodiment, and social acceptance' emphasizes the need for social acceptance and reducing unwanted attention, whereas 'Situational awareness and adaptability' and 'Selective information management' focus on enhancing intent communication and safety, as reflected in our research question.

3. Methodology

3.1. Research design

In line with the study's objective and the engaging framework developed by Bingqing Zhang et al., (Zhang et al., 2022) we adopted a co-design approach to foster empathy toward WUs among the research and development team. For this we have taken four steps: *Step 1*: We initially conducted a qualitative survey for WUs to collect their primary concerns related to eHMI. *Step 2:* We held a set of focus group discussions that encouraged interactive dialogue about eHMI priorities among participants from diverse backgrounds, including cognitive psychology, physiotherapy, design, and WUs themselves. This group setting was intended to facilitate rich discussions and feedback, contributing to an interdisciplinary exploration. Focus group discussions are widely used in qualitative research to deeply explore social dynamics and communication perspectives (Nyumba et al., 2018). We followed the Consolidated Criteria for Reporting Qualitative Research (COREQ), a common checklist for studies involving focus groups (Tong et al., 2007). *Step 3:* Included ideation sessions where participants actively shared their desired external interface for wheelchairs, and evaluated the proposed interface concepts to select the highest-ranked one for prototyping. These sessions encouraged collaboration and allowed participants to illustrate ideas for improving eHMIs that aligns with user priorities. *Step 4:* After the prototype is created, a group of experienced WUs and pedestrians assessed it and shared their viewpoints, helping us identify deficits and positive aspects of the proposed eHMI (Fig. 1). The study protocol was approved by the Human Research Ethics Committee, with certification number 30019494.

3.2. Participants

Inclusion criteria for all participants, including WUs, were: (1) aged 18 years or older; (2) willingness and ability to visually express design or interface-related ideas through hand-sketching or diagrammatic methods; (3) availability for in-person meetings; and (4) completion of a literature review provided by the authors on the challenges and user experiences related to mobility aids. The inclusion criteria for non-WUs were (5) being a registered Ph.D. or master's student, or a professional with expertise in cognitive psychology, physiotherapy, and design. Additional criteria for WUs included: (6) a minimum of three years of experience using a manual or powered wheelchair; and (7) regular engagement with diverse public and social environments (e.g., transit, public spaces). To ensure meaningful participation in design activities, (8) eligible WUs had no major cognitive, sensory, or upper-limb motor impairments affecting verbal or visual communication. The study excluded master's students and experts involved in parallel engineering studies on wheelchair development, as their focus on functional aspects might overshadow the communication and social factors among WUs, which are the primary focus of our study. Additionally, WUs who were undergoing medical visits were excluded to ensure that their health issues and mobility disability did not influence their participation, even for the qualitative survey. Potential participants were screened for eligibility and contacted.

3.3. Procedures

Step 1: Initially, responses to a qualitative survey were collected from 22 WUs (aged 32–55; mean age = 42; 10 males and 12 females). The main challenges they reported in urban settings were then grouped. At this stage, we did not suggest or emphasize any themes, as our intention was solely to use these concerns to inform the prompts for the subsequent focus group discussions.

Step 2: The focus group discussion began with a review of the qualitative survey responses and an examination of the general structure of PWs. To facilitate effective dialogue, we established clear guidelines for presenting prompts and encouraging discussion from diverse perspectives. The results of this section serve both as a reflective summary of insights from interdisciplinary discussions—presented as themes—and as a modular set of design considerations derived from these themes, adaptable to contextual and cultural needs. These considerations were shared with participants during the ideation sessions to guide and inspire clear, focused suggestions. In this step, 18 participants (aged 32–57; mean age = 39.25; 10 males and 8 females), including WUs with $\geq$ 5 years of wheelchair use experience, as well as experts attended the in-person focus group meetings (see Table 1).

Step 3: During the ideation sessions, we employed brainstorming and sketching techniques. These concepts primarily address three key states within the WUs' journey: 1) during yielding or when the wheelchair is at rest, 2), when the WUs initiates movement, and 3) when the WUs is cruising. For each wheelchair state, we considered scenarios to discuss potential solutions for safe and effective social communication. We also aimed to present possible solutions and design interventions for each scenario. Concepts also needed to be free of language or culture-specific elements, avoiding text or symbols tied to any culture. We prioritized the use of intuitive design elements and everyday metaphors to reduce cognitive load and enhance usability. By integrating familiar visual and interactive cues, the interface minimizes the need for users to learn a new system or symbolic 'language,' thereby supporting a more seamless and accessible user experience. Our designs were based on the most common PWs' models (All Star Wheelchair). Subsequently, the

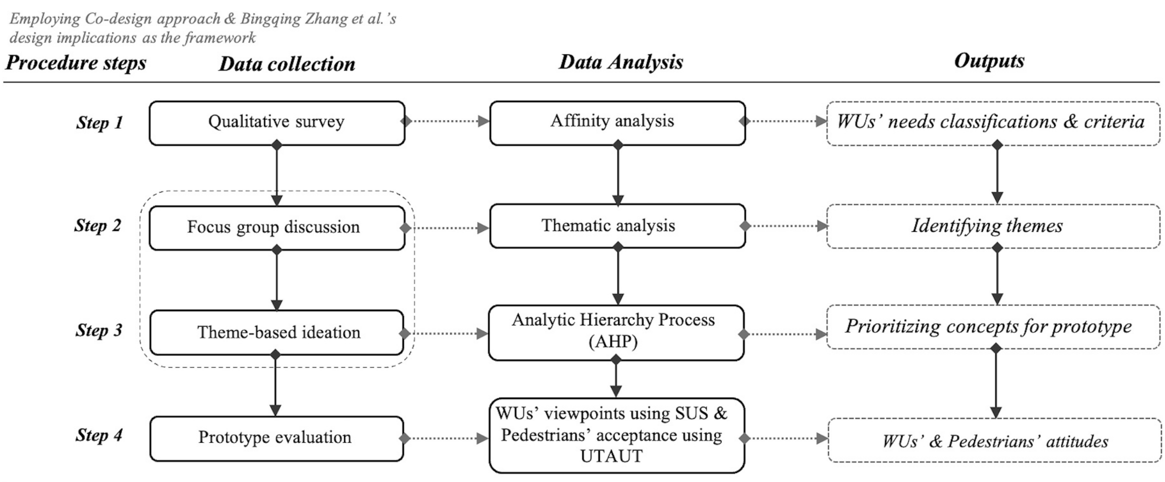

Fig. 1. The research design and procedure. © Image by Authors.

Table 1
Background and characteristics of focus group discussion's participants (N = 18).

Characteristic	(n), (%), median (min–max)	# of exploratory sketches
Age	39.25 (min–max: 32–57)	–
Profession area		Total of 85 pages, including:
Design	(n = 6), 33 %	35
Physiotherapy	(n = 3), 16.6 %	10
Cognitive psychology	(n = 3), 16.6 %	16
WUs	(n = 6), 33 %	24

interface concepts were reviewed and evaluated collaboratively by both participants and researchers. This assessment was guided by the themes identified in Step 2, which served as the criteria for the Analytic Hierarchy Process (AHP) (Vaidya & Kumar, 2006). Based on the participants' ratings, the highest-ranked concept was selected for further refinement and prototyping. This structured evaluation ensured that concept selection was both transparent and scientifically justified. By applying the AHP, we systematically translated the identified qualitative themes into quantitative evaluation criteria. This integration enabled data-driven prioritization of concepts aligned with the study's thematic goals. Consequently, the final concept reflected a synthesis of participant insights and broader design considerations, supporting a user-centered and methodologically robust design outcome.

Step 4: Within two weeks following the concept selection, the highest-rated interface design was translated into a functional prototype. This initial prototype was integrated onto the wheelchairs of participating users to simulate realistic usage scenarios. The evaluation phase involved two participant groups: WUs and pedestrians. A total of 12 WUs (5 males, 7 females; aged 39–62*;* mean age = 48*;* 1 to 22 years of wheelchair experience) and 27 pedestrians (15 males, 12 females; aged 33–51*;* mean age = 38.3) took part in the experimental sessions. Participants interacted with the prototype under controlled yet contextually relevant conditions to assess its effectiveness in real-time communication and social interaction.

3.4. Data collection

In this study, four sets of data were collected: (*Step 1*) qualitative surveys completed by WUs; (*Step 2*) focus group discussions; (*Step 3*) participant scores for concept evaluation; and (*Step 4*) feedback from WUs and pedestrians following the prototype assessment.

Step 1: The survey responses provide a data pool, that serves as the outline, used in focus groups discussion. The primary questions addressed in the qualitative survey were:

a) Have you encountered difficulties in social communication while using a wheelchair? please describe.
b) When faced with a challenging situation, do you typically seek assistance? If so, how do you communicate your request?
c) How important are the appearance and symbolic meaning factors (for communication) once you are using a wheelchair?
d) How does your wheelchair communicate with car drivers and pedestrians in navigating in the cities?
e) How would you describe your ideal wheelchair to navigate in an urban setting?

Step 2: A total of six focus group discussions and ideation sessions were conducted over a three-week period in August and September 2024. These sessions alternated and were held in person at a university laboratory, which was prepared in advance by the first author after securing the necessary permissions. Efforts were made to create a welcoming and inclusive environment, minimizing external judgment and peer pressure to encourage participants to express their ideas freely. Each session lasted approximately two hours, resulting in a total of 12 h for all six sessions. Each session involved six individuals: four participants (including two WUs and two domain experts in design, cognitive psychology, or physiotherapy) and two members of the research team who facilitated the discussions and actively directed the conversation. The authors reflected on the guiding questions for the discussions (see Appendix I for details).

During the focus group discussions, the first author guided the conversations according to the study's objectives, while the second author facilitated and organized the discussions, documenting key insights. The second author ensured that all important points were carefully recorded. When a point showed potential for further exploration, the first author encouraged deeper dialogue to foster richer and more focused exchanges among participants. The authors made a concerted effort to capture the interdisciplinary nature of the issues, consider counterarguments to dominant claims, and identify insights that aligned with the development of the eHMI and the study's overall aims. These structured yet flexible sessions provided rich interdisciplinary dialogue, grounded in participants' lived experiences and professional insights. Multimodal insights were documented through audio recordings, field notes, and photographs, enabling a comprehensive understanding of participants' cognitive processes, creative reasoning, and socio-emotional responses. The key themes emerging from the discussions were synthesized and used to inform participants' ideation processes, which were further developed into the final interface concepts.

Step 3: In the ideation sessions, the primary focus was on the ideation phase, where both verbal and visual contributions were recorded for analysis. Verbal data included participants' spoken reflections, critiques, and discussions around the design concepts, while visual data encompassed sketches, diagrams, and annotated ideas produced during the ideation activities. The emerging concepts were then discussed using the *Criticism of Interface Aesthetics* (CIA) framework (Bertelsen & Pold, October 2004), which offers a structured approach to analyzing the aesthetics of human–computer interfaces. This model provides valuable insights into the visual perception of wheelchairs. Its first component—stylistic references—involves analyzing aesthetic influences in interface design and has broad applicability across disciplines such as graphic and industrial design (Faraji & Valajoozi, 2014; Rasouli Valajoozi & Zangi, 2016); architecture, and interior design (Bertelsen & Pold, 2004; Cucuzzella et al., 2024). Based on these discussions, the finalized ideas and concepts were rendered using 2D and 3D design software. To evaluate the concepts, 18 participants and two authors took part in a final session, during which they discussed each concept and reached a consensus. Based on these discussions, mean scores—reflecting participants' average ratings—were determined and used as input for the AHP evaluation model (Vaidya & Kumar, 2006).

Step 4: Initially, the prototype was installed on users' wheelchairs, and participants were introduced to the eHMI components to help them understand the user interface. We then asked participants, including WUs and those in the role of pedestrians, to spend 5–10 min participating in our experiment. Accordingly, we designed an experiment for participants to share their viewpoints toward the prototype. In this experiment, we aimed to demonstrate and evaluate scenarios where WUs and pedestrians interact using the proposed eHMI. While testing was held in a residential complex's indoor parking lot rather than on actual streets, we aimed to provide participants with an immersive first-person experience using our wheelchair-mounted prototype. The evaluation procedure was conducted over several days and spanned a two-week period.

3.5. Data analysis

The analysis consists of four sections: classification of survey responses, thematic analysis of discussions, evaluation and prioritization of concepts, and prototype assessment by both WUs and pedestrians.

Step 1. Analysis of survey responses: In this step, we have used the *affinity analysis* to organize number of ideas and responses (WUs: N = 22) provided by qualitative survey. This method also helped participants (N = 18) to organize a large number of ideas by grouping them into natural relationships (Affinity, 2024). This method is used to generate, organize, and consolidate information related to a product, process, complex issue, or problem. After generating ideas, we categorized them based on their affinity or similarity.

Step 2. Analysis of discussion: We conducted a structured analysis of the discussion sessions based on Braun and Clark's six-phase inductive *thematic analysis* framework. This approach consists of sequential stages: data familiarization, generation of preliminary codes, thematic identification, theme review, defining and naming the themes, and producing a report (Braun & Clarke, 2012). Two independent coders initially analyzed the concepts separately. Inter-coder reliability was then established through regular discussions and consensus meetings, during which discrepancies were resolved and main insights and concepts (screening) were categorized (Kudrowitz et al., 2012) followed by the construction of preliminary themes. Both semantic and latent interpretation strategies were employed to identify broader themes (Braun & Clarke, 2022); involving the organization, comparison, and analysis of coded excerpts for repetitions, similarities, differences, and gaps. Themes were refined through critical discussion and consensus to reduce subjective bias and ensure consistency. Reflexivity was maintained throughout, with researchers acknowledging and reflecting on their potential biases during interpretation. Participants clarified their thoughts in group discussions and briefly described their ideas for validation.

Step 3. Concept evaluation: Following the ideation process, the finalized ideas and concepts were evaluated using the AHP, a structured decision-making method designed to prioritize and compare complex, multi-criteria options effectively (Vaidya & Kumar,

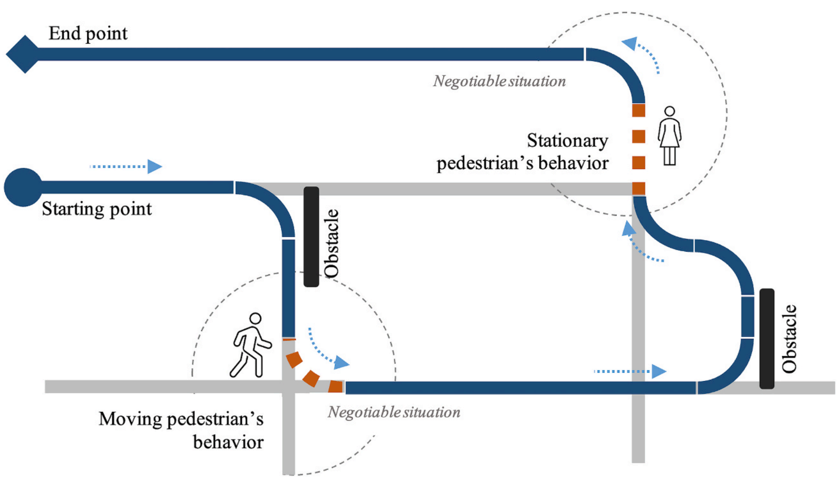

Fig. 2. The experimental routes include WUs' behaviors and interactions with pedestrians.

2006). In the AHP process, six steps were taken; including Step 1: Define the problem and Criteria, 2: Define Alternatives, 3: Establish priority amongst criteria and alternatives using pairwise comparison, 4: Checking consistency amongst the pairwise comparisons, 5: Evaluating relative weights from the pairwise comparisons and getting the calculated overall priorities for the alternatives, and 6: Performing Sensitivity Analysis (Step, 2023). In the AHP, the Consistency Ratio (CR) ensures the consistency of pairwise comparisons. A CR below 0.1 (10 %) is acceptable (Malczewski, 1999); if it exceeds this threshold, judgments are inconsistent and may need revision (Pourghasemi et al., 2012). In our model, the emerged themes—organized into groups during Step 1—served as the evaluation criteria, and the finalized design concepts were defined as the alternatives. For detailed calculations, please refer to Appendix II and III. A & B.

Step 4. Prototype assessment: After finalizing and refining the prototype, we focused on evaluating the attitudes of both WUs and pedestrians, the usability of the wheelchair equipped with the prototype, and its potential psychological impact. In this regard, the *viewpoints of WUs* and *pedestrians* were assessed as follows:

Viewpoints of WUs: In this part, WUs were asked to navigate an experimental route marked by white arrows on the ground, designed to simulate interactions with barriers and pedestrians (Fig. 2). The route included two physical objects and two pedestrians as obstacles. The obstacles required the user to select specific options to indicate their state, whether risky or fine, showing the WUs' intentions to pedestrians. They also needed to perform tasks such as avoiding obstacles or turning. In interactions with pedestrians, WUs

Table 2
Design suggestions and implementations and their relevance to the three states of the wheelchair.

Criteria: Themes	Design suggestion	Implementation and considerations	Yielding/ at rest	Initiating	Cruising
Communication: Theme I. Streamlined Information in Interaction	Bright, high-visibility LED indicators with universal icons (e. g., arrows, stop signs).	Large LED arrow indicates wheelchair direction	NA	●	◦
	Small screen display with brief messages or symbols.	Use red "STOP" or green "GO" symbols instead of lengthy text.	NA	◦	●
	Use widely recognized traffic symbols and colors.	Use caution symbols like a yellow triangle or a green pedestrian icon for safe crossing.	◦	●	●
	Coherent light patterns reflecting wheelchair status/actions.	Blink arrows sequentially to indicate turn preparation and execution.	NA	◦	●
	Display offering full context of wheelchair movements.	Use visual indicators and text (e.g., "Turning Left" with an arrow) along with real-time feedback (e.g., "Speed Reduced").	◦	●	●
Safety: Theme II. User-Centric Safety Feedback	Lock/confirm certain controls to prevent accidental use.	Add a "confirm" button and two-step activation for critical functions.	●	◦	●
	Position eHMI controls for easy, natural access.	Position controls on armrests, angled for natural hand placement.	NA	●	●
	Use large, distinct icons and labels.	Use symbols like a red "X" for stop, green "checkmark" for activation, and blue "gear" for settings with tactile/visual feedback.	NA	◦	●
	Create a simple, grouped control layout.	Cluster controls by function with distinct sizes and shapes for easy use.	NA	●	●
	Make the control panel height- and angle-adjustable	Include a sliding/pivoting mechanism to adjust the control panel's position.	NA	●	●
	Add backlighting for low-light visibility.	Implement adjustable LED backlighting for clear visibility in various lighting.	●	●	●
	Proximity Warning Lights	Use LED lights that change color (green, yellow, red) based on obstacle proximity for navigation safety.	◦	●	●
	Real-Time Status Indicators	Display mode on the external interface with alerts for critical conditions.	NA	◦	●
Aesthetics: Theme III. Harmonious and Minimalist Interactions Design	Choose a functional, appealing and harmonic color palette.	Use a high contract color panel on eHMI for high visibility.	NA	NA	NA
	Add variety of textures for visual interest.	Combine soft-touch rubber handles with contrasting metal finish on eHMI for a modern look.	NA	NA	NA
	Use abstract, readable icons and text.	Design clean-line icons with sans-serif fonts, ensuring consistent spacing.	NA	◦	◦
	Ensure eHMI design matches the wheelchair.	Match eHMI shapes and finishes with the wheelchair's design.	NA	NA	NA
	Keep symbols recognizable and clear.	Use minimalistic symbols with ample spacing for clarity.	NA	◦	●
Feasibility: Theme IV. Effortless Integration and Production	Design a tool-free, quick-connect eHMI.	Use snap-fit or quick-release components with a clear, visual guide for easy eHMI installation.	●	NA	NA
	Use lightweight, durable materials for comfort and maneuverability.	Use carbon fiber or high-strength aluminum for a lightweight, durable eHMI casing, and design compact internal components.	◦	●	●

needed to communicate their intentions. We aimed to assess the WUs' behavior in responding to different negotiable situation that indirectly convey by eHMIs. To evaluate the experiment, we used the System Usability Scale (SUS) to assess the wheelchair's usability (Brooke, 1996). Immediately after the experiments, participants' attitudes towards the proposed eHMI interaction were measured using a modified questionnaire from Xiaochen Zhang et al. (Zhang et al., 2024). Participants rated nine statements using a five-point Likert scale (1 = strongly disagree, 5 = strongly agree). Further details are provided in Appendix IV.

Viewpoints of pedestrians: We aim to assess pedestrian acceptance when interacting with a wheelchair equipped with our prototype. Participants role-playing pedestrians engaged from a first-person perspective, both stationary and moving. To measure pedestrian acceptance, we used a modified questionnaire based on the Unified Theory of Acceptance and Use of Technology (UTAUT) model, which includes dimensions such as performance expectancy, effort expectancy, and intentions (Rahman et al., 2017). Relying on the questionnaire from Xiaochen Zhang et al. we assessed pedestrians' attitudes toward the wheelchair equipped with our eHMI prototype (Zhang et al., 2024) (see Appendix V for details).

4. Results

Using affinity analysis, four criteria were identified in the qualitative survey including, communication, safety, aesthetics and feasibility. Accordingly, communication and safety were considered as the primary criteria, and aesthetics, and feasibility were categorized as the secondary criteria. The notion of communication, which involves the transmission of verbal and non-verbal messages (Munodawafa, 2008), in this context, refers to developing a means to understand the situation and intentions of WUs from the perspective of pedestrians and drivers. In the context of user-product interaction, safety, defined as the absence of any undue threat to human life or health (Report on International Consumer Product Safety Risk Assessment Practices, 2016), refers to providing opportunities to improve the user-wheelchair interaction, mitigate risks, and ensure the security of WUs. Product design aesthetics involve understanding the complexity of visual and non-visual elements (Hekkert & Leder, 2008; Rasoulivalajoozi et al., 2025b) and achieving a harmonious visual appeal using those principles (Faraji & Valajoozi, 2014). Feasibility means the evaluation of whether a proposed concept is legally and technically possible and economically justified (Simplilearn Feasibility Study and Its Importance in Project Management, 2023). Each of these criteria was used as a basis to identify the corresponding themes in group discussions. Through group discussions, 43 codes were extracted, and a single theme emerged for each category of criteria, ultimately identifying four distinct themes:

- Streamlined Information in Interaction;
- User-Centric Safety Feedback;
- Harmonious and Minimalist Interaction Design; and
- Effortless Integration and Production.

Then, design suggestions and implementations were provided for each theme, with their relevance to the wheelchair's three states—yielding/rest, initiating, and cruising—identified (Table 2). This table guided our ideation process throughout the study; however, not all suggestions were directly implemented in the final design concepts. Rather, the suggestions serve as a modular design consideration pool that others can adapt based on context-specific needs—such as varying regulations and interaction patterns in street and urban settings across different countries, community norms surrounding assistive devices, individual user preferences, and broader cultural and social factors. We propose that Table 2 can support future research and practice by offering a structured yet flexible set of design considerations. It can also act as a foundation for identifying which communicative features may benefit from standardization to ensure consistent and recognizable signaling across various wheelchair platforms and their integrated communication systems.

During the ideation, participants mostly emphasized the absence of adequate external surfaces on PWs to accommodate eHMIs.

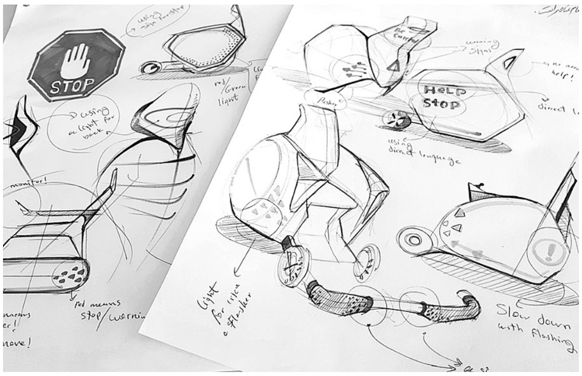

Fig. 3. A sample of exploratory sketches.

Accordingly, they tried to add external surfaces as an opportunity to introduce a broader range of innovative and efficient eHMIs. This led to the generation of 85 pages of exploratory sketches, which were then organized into 12 primary themes (see Fig. 3). Following this categorization, a screening process identified five key concepts. The presented concepts include 'WheelGlow Assist,' 'WheelSafe Illumina,' 'PathGuard Illumina,' 'Safeguard Sonic,' and 'Handle Illumina'. Following are the descriptions of these five concepts.

4.1. Concepts

In this section, five concepts are introduced along with their general features. Concept 2 is described in greater detail, as it was ultimately chosen by the participants.

Concept 1. WheelGlow Assist: Inspired by traditional traffic signals into the wheelchair's frame, integrating red for urgent need of

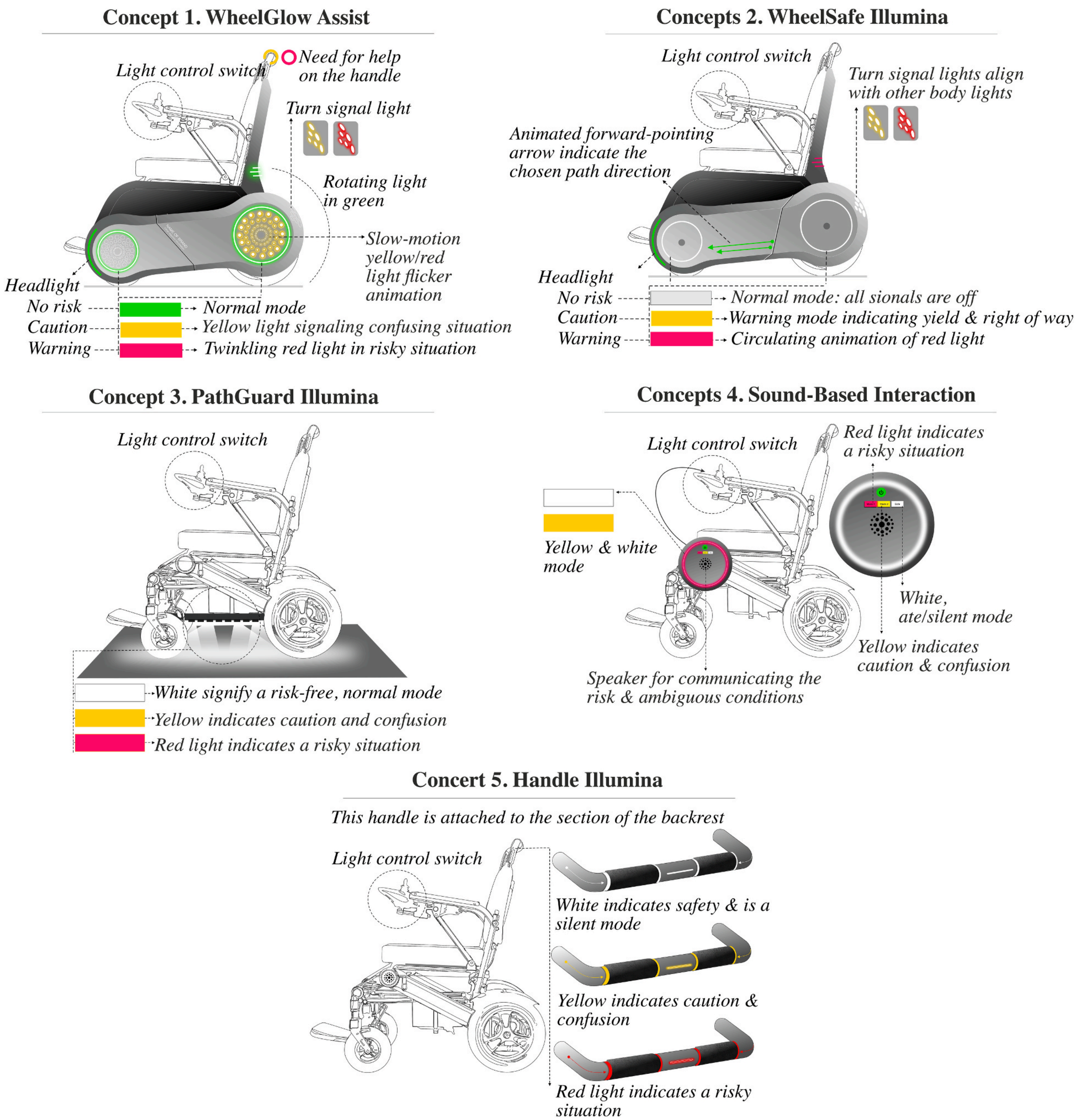

Fig. 4. Five proposed concepts. © Image by Authors.

assistance, yellow suggests uncertainty and invites help, and green lights signifies safe and unobstructed mobility. When turning, the light blinks red to signal direction. In emergencies, users can activate a flashing red light for help, while a circulating green light indicates comfortable movement. The animated green light stays on even when stationary, offering continuous feedback on the wheelchair's status and intentions (see Fig. 4, Concept 1).

Concepts 2. WheelSafe Illumina: This concept uses arrow lights to convey the user's movement intentions. In normal mode, only the turn signals and blue front/back lights are illuminated, indicating no issues or need for assistance (see Fig. 4, Concept 2). In caution mode, a yellow stop signs light blinks (specifically visible to drivers), and simultaneously, a blue animated arrow moves from back to front. This indicates that while the user is managing their movement independently, caution is needed, and others should stay alert or help if necessary. In critical situations, a rapidly twinkling red light indicates the need for immediate assistance. In this mode, the hand and blue arrow lights are off, indicating the user is capable of handling their movement. Users manage all settings via a control panel on the armrest, aligned with the lights on the wheelchair. Effective day and night, this concept clearly communicates with pedestrians, drivers, and users, but selecting the correct light is crucial to avoid confusion.

Concept 3. PathGuard Illumina: A ground light projection, similar to eHMI, is used. A red light signals a need for assistance, while a twinkling yellow light indicates road crossing, with faster twinkling showing increased caution. A white light means no assistance is needed. Effective at night but less distinct in daylight, this cost-effective solution relies solely on floor light projection and can be used on various PWs, even without external surfaces. However, it is limited to conveying simple messages and may not support complex interactions (see Fig. 4, Concept 3).

Concept 4. Safeguard Sonic: This concept uses sound-based interactions, with three distinct sound effects. An affixed device emits a continuous alarm and flashing red light in emergencies. A specific sound alerts others to potential risk, while silence indicates safety with no need for assistance. Distinct alarms stand out in noisy areas, and the Doppler Effect enhances perception of direction and urgency (Isoardi, 2023) (see Fig. 4, Concept 4).

Concept 5. Handle Illumina: Compatible with all wheelchair types, this back-handle accessory signals assistance with a twinkling red light for urgency, a rhythmic yellow light for caution, and a white light for nighttime visibility. However, rear-only visibility may limit communication with drivers from the side or front (see Fig. 4, Concept 5).

4.2. Concept evaluation

Using the AHP method for defining criteria, the weighted scores for the identified themes were distributed as follows: 56.4 % for communication, 28.0 % for safety, 9.9 % for aesthetics, and 5.7 % for feasibility, with a consistency ratio (CR) of 8.8 % (see Table 3 and Appendix III. A & B). Results show that Concept 2: 'WheelSafe Illumina' ranked highest (41.3 %), followed by Concept 1: 'WheelGlow Assist' (28.1 %). These two concepts use external surfaces for better communication between WUs and their surroundings. Concept 3: 'PathGuard Illumina' ranked third (13.0 %). Concepts 5: 'Handle Illumina' (5.7 %) and 4: 'Safeguard Sonic' (11.8 %) ranked lowest (see Fig. 5). However, integrating these with top-ranked concepts could enhance multisensory communication, improving safety without drawing unnecessary attention or causing discomfort to users. Fig. 6, A, illustrates a further development of Concept 2, and B, its prototype.

After selecting Concept 2, WheelSafe Illumina, prototype development began. During this phase, we adjusted and optimized the concept based on feedback from the evaluation. The results of the WUs' attitude questionnaire—SUS questionnaire—shown in Fig. 7, indicate that most participants had a positive view of the proposed eHMI for wheelchairs, demonstrating openness to accept and install on their wheelchairs. Participants expressed satisfaction and trust in the safe navigation (67 %) and effective communication features of the proposed eHMI (75 %). However, some participants indicated that they did not entirely rely on the eHMI (58 %), occasionally preferring to use their body gestures. Participants also felt that the eHMI did not attract significant unwanted attention (59 %), making

Table 3
AHP evaluation of five proposed concepts based on the weight of each criterion.

	Criteria: Themes			
Name of Concepts (C)	*Communication*: Theme I. Streamlined Information in Interaction	*Safety*: Theme II. User-Centric Safety Feedback	*Aesthetics*: Theme III. Harmonious and Minimalist Interactions Design	*Feasibility*: Theme IV. Effortless Integration and Production
C1. WheelGlow Assist	30.1 %	25.9 %	32.7 %	15.8 %
C2. WheelSafe Illumina	43.2 %	44.1 %	46.1 %	15.8 %
C3. PathGuard Illumina	11.9 %	9.4 %	12.3 %	34.4 %
C4. Safeguard Sonic	10.4 %	16.6 %	3.9 %	9.6 %
C5. Handle Illumina	4.4 %	4.0 %	5.0 %	24.4 %
Consistency Rate (CR)	4.7 %	5.1 %	8.4 %	1.9 %

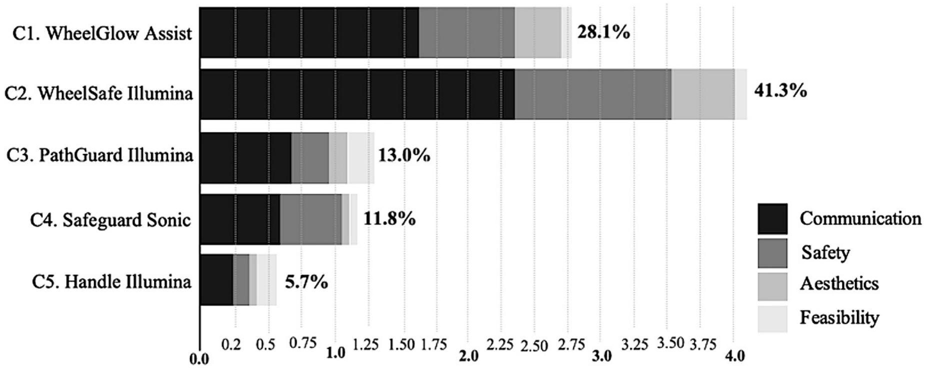

Fig. 5. The final AHP evaluation of five proposed concepts.

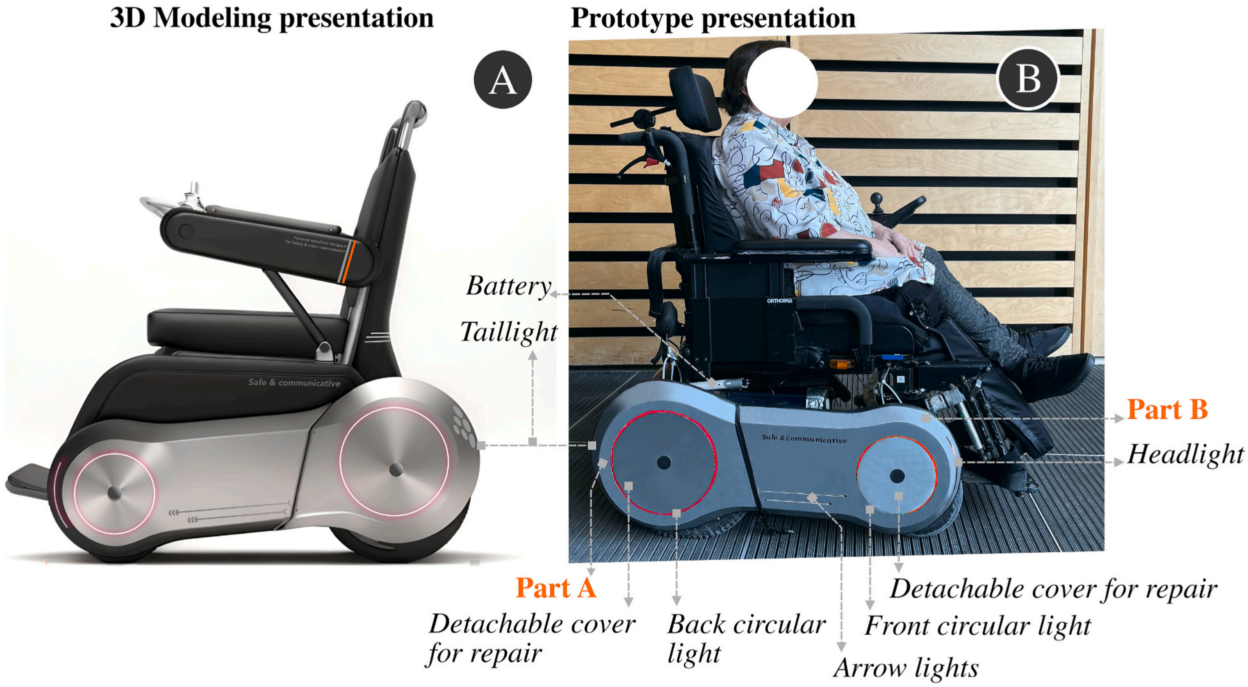

Fig. 6. The final Concept 2: 3D modeling presentation of WheelSafe Illumina. B: Prototype presentation.

them comfortable using it, though some remained somewhat concerned about such attention (41 %). In contrast, when considering direct interaction with WheelSafe Illumina and potential risks associated with its use, participants expressed a willingness to use it in the future (75 %), as indicated by responses to reverse Question 5. They largely viewed the proposed eHMI as a useful improvement over their current wheelchairs, appreciating the ease of control and the enjoyment it provided during use (67 %). In the last two reverse questions, participants further confirmed their positive assessment by disagreeing with statements about inconsistency (75 %) (Q8), and unnecessary complexity or loss of independence when attaching WheelSafe Illumina (84 %) (Q9).

The pedestrian acceptance questionnaire results shown in Fig. 8 indicate that most participants had a positive attitude toward the proposed eHMI. Pedestrians believed that the WheelSafe Illumina could help pedestrians react more quickly to unsafe walking conditions while crossing the road (67 %). Additionally, they expressed that interaction features on eHMI-equipped wheelchairs would lower the risk of an accident (78 %). While participants found this interaction with the proposed eHMI easy to learn (59 %), some still found it ambiguous to decode the signs (41 %), showing a potential in providing a communicative property. However, in general interaction, participants had no hesitation to cross the road when the WheelSafe Illumina is attached to wheelchairs in operation (70 %) (Q4) and felt comfortable crossing the road in front of eHMI-equipped wheelchairs (74 %).

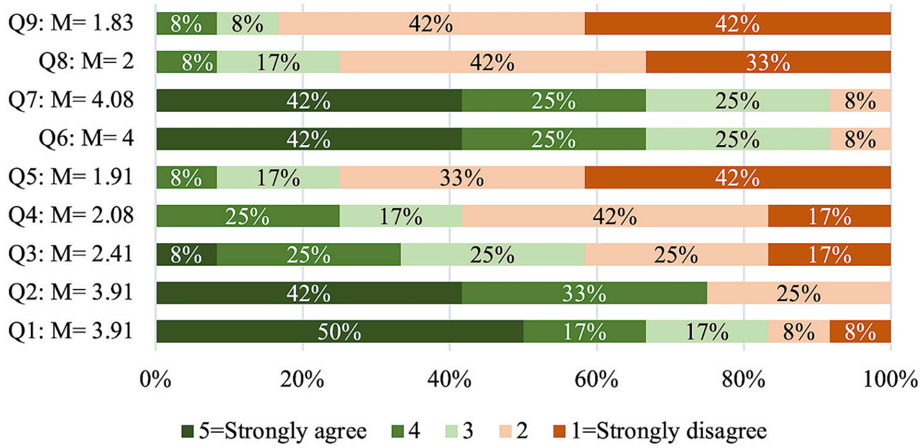

Fig. 7. WU's viewpoint on proposed eHMI: WheelSafe Illumina (N = 12). Q means Question number. (Q 3 is neutral and 4, 5, 8 and 9 are reversed questions).

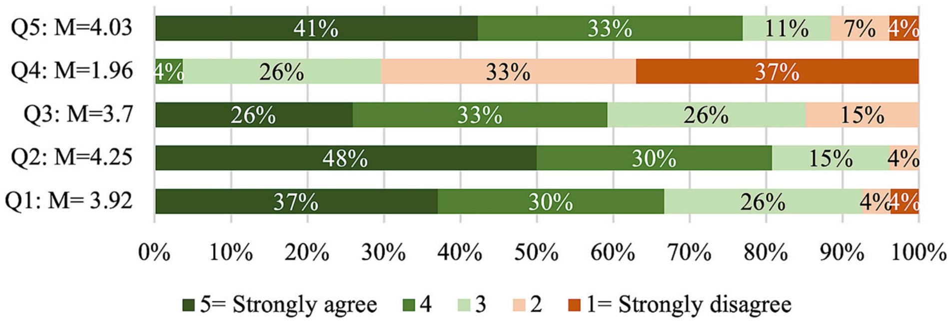

Fig. 8. Pedestrians' acceptance of proposed eHMI: WheelSafe Illumina (N = 27).

5. Discussion

5.1. Integrating shell structures to improve aesthetics and social acceptance

In this study, Concept 2 and Concept 1, prioritized highest, and utilizing external surfaces, introduce novel approaches to intent communication, whereas Concepts 3, 4, and 5 build upon existing possibilities. This aligns with previous research showing that external coverings can effectively convey a product's language (Hernández et al., 2018). It is worth noting that many wheelchairs lack external covers, emphasizing structural elements like struts, frames, and joints. According to Lidwell and et al., structures can be categorized into three formats: mass structures (e.g., dams and adobe walls), frame structures (e.g., bicycles and skeletons), and shell structures (e.g., bottles, airplane fuselages, and domes) (Lidwell et al., 2010). A shell structure is an outer layer that encloses and protects internal components while enhancing aesthetic form. It is designed to be strong yet lightweight, efficiently distributing loads and serving as the product's visual and tactile interface (Farshad, 1992; Sharma, 2025). In light of this, using a shell structure, such as covering the wheel or motor, enhanced the wheelchair's aesthetics and facilitated the integration of visual cues for better social acceptance and communication (Lanutti et al., 2015; Rasoulivalajoozi et al., 2025a;b). This is highlighted in themes I, III, and IV and their design suggestions, which create clear and concise designs that are functionally efficient. These designs are harmonious and easily integrated into existing systems and processes, allowing for ease of implementation.

Furthermore, in Concept 2 and 1 concealing the bulky mechanisms of the wheelchair may help counteract the stigma associated with its size—as emphasized in prior studies (Asha et al., 2021; Rasoulivalajoozi & Farhoudi, 2025). For instance, Xiaochen Zhang et al.'s study highlighted this challenge, where the eHMI's ground illumination drew undue attention, increasing social discomfort for WUs (Zhang et al., 2024). Although the proposed eHMI in our study could mitigate unwanted attention, we believe the issue extends beyond the argument surrounding eHMI and involves the symbolic role of the wheelchair as an icon of disability (Barbareschi et al., 2021; Mokdad et al., 2018). This necessitates defining design principles that address the socio-emotional needs of WUs and applying them in wheelchair development (Rasoulivalajoozi et al., 2025c). Researchers can explore the role of aesthetic design criteria in shaping the external appearance of wheelchairs to enhance users' social empathy and communication, as addressed in Themes I and III.

5.2. Safety and communication aspects

This study emphasized the importance of transparent communication in the proposed eHMI, consistent with previous research demonstrating that transparency enhances trust, safety, and acceptance in driving systems (Detjen et al., 2021). The WheelSafe Illumina improves system transparency by adding dynamic visual cues to the wheelchair's shell, clearly conveying the WU's intent to drivers and pedestrians in negotiable situations. The prototype test revealed that although most WUs are satisfied with the proposed eHMI, its effectiveness in complex situations is limited. A portion of participants (58 %) still occasionally prefer using body gestures rather than relying solely on the eHMI. This suggests a possible skepticism toward the eHMI's ability to accurately convey intended messages to drivers or pedestrians. As body language is more inclusive and typically used, they find body language and eye contact more effective in navigating these situations (Dey, 2020). In this context, the receivers of the message should be near WUs, therefore the distance between WUs and others, whether pedestrians or drivers, also plays a crucial role in conveying the intended message. Future studies could explore the role of body gestures and the impact of distance on communication between WUs and their environment.

In addition, maintaining a balance between accuracy and the number of visual cues on the shell structure is essential to prevent confusion. This is particularly true when considering potential audio cues, as Theme III highlights the need to minimize clutter and complexity. While the combination of visual and audio cues may offer benefits, previous research suggests caution regarding audio cues emitted from wheelchairs due to perceived stigmatization (Asha et al., 2021). Therefore, if audio cues are to be integrated, careful sound design is necessary. The combination of visual and haptic feedback design modalities shows promise for AV and PW interaction (Asha et al., 2021; Mahadevan et al., 2018; Towards Inclusive External Communication of Autonomous Vehicles for Pedestrians with Vision Impairments, 2020). This is also emphasized in our study, in Theme II, User-Centric Safety Feedback, which prioritizes user safety in interactions with PWs. Although haptic feedback design was not incorporated into the prototype due to implementation constraints, future research could investigate its potential contribution to wheelchair design.

Additionally, our experiment found that pedestrian participants felt WheelSafe Illumina improved reaction times and reduced risk (67 %). This aligns with research showing that pedestrian awareness of WUs' intentions leads to smoother movements compared to scenarios without communication (Morales et al., 2015). However, some participants (41 %) found WheelSafe Illumina ambiguous when crossing roads, likely due to the simultaneous use of multiple dynamic visual elements. This lack of clarity and complexity may confuse pedestrians and cause them to miss the interaction, reducing user confidence. This issue can also likely stem from insufficient training time and a lack of standardization and consensus in eHMIs, as noted in arguments against eHMI (de Winter & Dodou, 2022). We hope that more consistent and inclusive visual elements for wheelchair eHMI will clarify these signs and improve effectiveness. Also, this can be improved by reducing the number of signs and optimizing visual priorities. While the bright primary color scheme was chosen to enhance sign visibility and ensure clarity, adding words and more visual elements on external surface could further reduce confusion among pedestrians and improve their ability to interpret intentions.

6. Conclusion

In this study, we collected data from WUs and engaged them, along with relevant experts, in focus group discussions and the design process. This led to the identification of key criteria and four themes. During co-design sessions, we applied design implications from Bingqing Zhang et al. outline the main aspects of eHMI for wheelchairs, aligning with our study's aims and addressing limitations in previous research. Following the evaluation of five concepts, Concept 2 (WheelSafe Illumina) was ranked highest and selected for prototyping. This concept aimed to enhance communication for both users and pedestrians, reduce the cognitive load of WUs, provide a more autonomous and personalized navigation experience, and mitigate unwanted attention and distractions caused by WUs' focus on the eHMI with light projection on the ground. The experiment evaluating WUs' viewpoints and pedestrian acceptance highlighted the appeal, safety, and communication of WheelSafe Illumina, but raised concerns about the consistent use of the eHMI. While WUs found the interface improved communication, and safety, and did not increase negative attention, some still preferred using body language for accuracy. Pedestrians felt that the interface enhanced their safe interaction with WUs, but some found the signs ambiguous, indicating a need for more training and universal communicative signs in developing eHMIs. Overall, although on-ground projection eHMI provides safety, assistance, and maintains users' attention on the route, our study found that integrating a shell structure with eHMI on the wheelchair also promotes a supportive attitude toward WUs. This approach, often overlooked in previous research, was effectively addressed through our co-design approach throughout the study. Notably, while eHMI with a shell structure and aesthetic considerations partially addresses WUs' socio-emotional needs, the issue extends beyond eHMI alone; a semantic turn and redesigning the wheelchair as an icon of disability with a socio-emotional polish could further enhance its social interaction.

6.1. Limitations and future studies

This study assessed WUs' and pedestrians' interactions in a simulated indoor parking environment to ensure safety and controlled testing during the prototype phase. While this setting provided insights into visibility, intuitiveness, and perceived social comfort, it did not capture the complexities of real urban contexts—such as interactions with drivers and unpredictable environmental factors. Future research should deploy WheelSafe Illumina in outdoor settings to evaluate its effectiveness across diverse traffic conditions and social scenarios, including driver behavior, mobility dynamics, and sensory distractions.

This study is limited by its reliance on subjective questionnaires to assess pedestrian-WU interactions, without incorporating objective behavioral data such as avoidance distance, decision-making time, motion capture, eye tracking, or WU operation error rates.

While these measures could provide a more comprehensive understanding, they were beyond the scope of our study. Future research could integrate these objective metrics to further validate or challenge the findings and provide deeper insights into pedestrian-WU dynamics.

While the integration of a shell structure into wheelchair interfaces has been positively received in terms of aesthetics and perceived social acceptance, it is essential to consider additional dimensions that may influence feasibility and broader adoption. From a technical perspective, materials such as lightweight composites or thermoplastics could offer structural durability while preserving mobility performance. Given the potentials of mass production, the cost of this shell structure could be reduced, making it more affordable for users, and it can be optimized for attachment to various wheelchair models. On the other hand, functional constraints must be addressed. For example, a shell structure might limit customizability or hinder accessibility for users who require modular support systems or frequent maintenance access. Therefore, future iterations of this concept should undergo comprehensive user testing and cost-benefit analyses to carefully balance form, function, and inclusivity. Future studies should compare our eHMI with concepts introduced by Xiaochen Zhang et al. (Zhang et al., 2024) and explore integrating their features. While the social considerations were emphasized in the focus group discussions as well as the proposed eHMI (de Winter & Dodou, 2022), we were not able to eliminate the iconic role of the wheelchair as a symbol of disability (Rasoulivalajoozi et al., 2025a). The iconic role of the wheelchair requires further investigation in socio-emotional design studies.

7. Disclosure

The author confirms that the abstract and full-text of this research has not been presented at any other journal, symposiums, conferences, or events.

The article's publication has been explicitly approved by the authors at the institution where the work was conducted. If accepted, the article will not be published elsewhere in the same form, in English, or any other language, including electronically, without the written consent of the copyright holder.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT Open AI in order to improve the writing. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article

CRediT authorship contribution statement

Mohsen Rasoulivalajoozi: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization, Data curation, Resources, Validation. **Morteza Farhoudi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Formal analysis, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2025.05.036.

Data availability

The authors do not have permission to share data.

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